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Tod A. Laursen, PI

Henri P. Gavin, Co-PI

Lawrence N. Virgin, Co-PI

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Department of Civil and
Environmental Engineering
Duke University
Durham, NC 27708-0287

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14. ABSTRACT
This project has represented an integrated modeling and experimental effort, with the following objectives:

1. experimental characterization of the dynamics of both total and partial frictional slip;
2. development of corresponding numerical strategies for treatment of such slip between elastically compliant structural members, exploring friction models and corresponding numerical strategies; and
3. use of the results of 1) and 2) to investigate prediction of damping characteristics in idealized frictional damping connections

In meeting these objectives, fundamental advances have been made in friction modeling, connecting continuum mechanical models for friction with experimental measurements of friction damping at the microscale. An effective tool has been provided for accurate prediction of damping associated with dynamical turbine blade behavior

15. SUBJECT TERMS

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1. Objectives

As detailed in past progress reports, this project represents an integrated modeling and experimental effort having the following objectives:

1. experimental characterization of the dynamics of both total and partial frictional slip;
2. development of corresponding numerical strategies for treatment of such slip between elastically compliant structural members, exploring novel friction models and corresponding numerical strategies; and
3. use of the results of 1) and 2) to investigate prediction of damping characteristics in idealized frictional damping connections, in a “capstone” experimental and numerical collaboration involving researchers from this project as well as that led by E. Berger of the University of Cincinnati

Through these objectives, this study aimed to provide fundamental advances in friction modeling, with the aim of providing models for friction proposed in the language of continuum mechanics of interfaces. The intention is to facilitate the prediction of dry friction structural damping by direct simulation of interface physics, such as are needed for the accurate prediction of damping associated with dynamical turbine blade behavior.

2. Status of Effort

Since this project was funded in March of 2002, the project has proceeded on schedule and in a manner consistent with the plan of work given in our original proposal. Our efforts in the past year (which included a no-cost extension from December 31, 2004 until June 30, 2005) were particularly significant, in that the desired integration between the numerical modeling effort and the experimental part of the project was convincing achieved. In particular, we were able to very accurately calibrate our microslip, Hertzian experiment (with dry friction involving steel-on-steel), and were also able to successfully predict complex hysteresis loops measured in particular slip situations, by using the *mortar-based* finite element contact analysis methods developed earlier in this project. More detail on these developments will be given in Section 3 of this report.

As discussed in our original proposal, the research approach we utilize emphasizes the systematic application of large scale, high fidelity computational approaches (based on the finite element method) to predict interface physics in complicated dynamical systems. Throughout the performance of this contract, our work has been performed while in regular contact with the project headed by E. Berger of the University of Virginia (formerly of the University of Cincinnati). This collaboration has been important, as the fracture mechanics analogies and low order dynamical models under consideration by that group can be contrasted with our high fidelity finite element descriptions in their relative ability to predict interface damping characteristics. The shear lag based experiments featured by that research group are also an ideal complement to the results generated in our study, since they quantify the spatial and temporal distribution of frictional dissipation on an interface of finite extent (in contrast to our experiment, which investigated dissipation of a highly localized nature, effectively in a Hertzian contact patch).

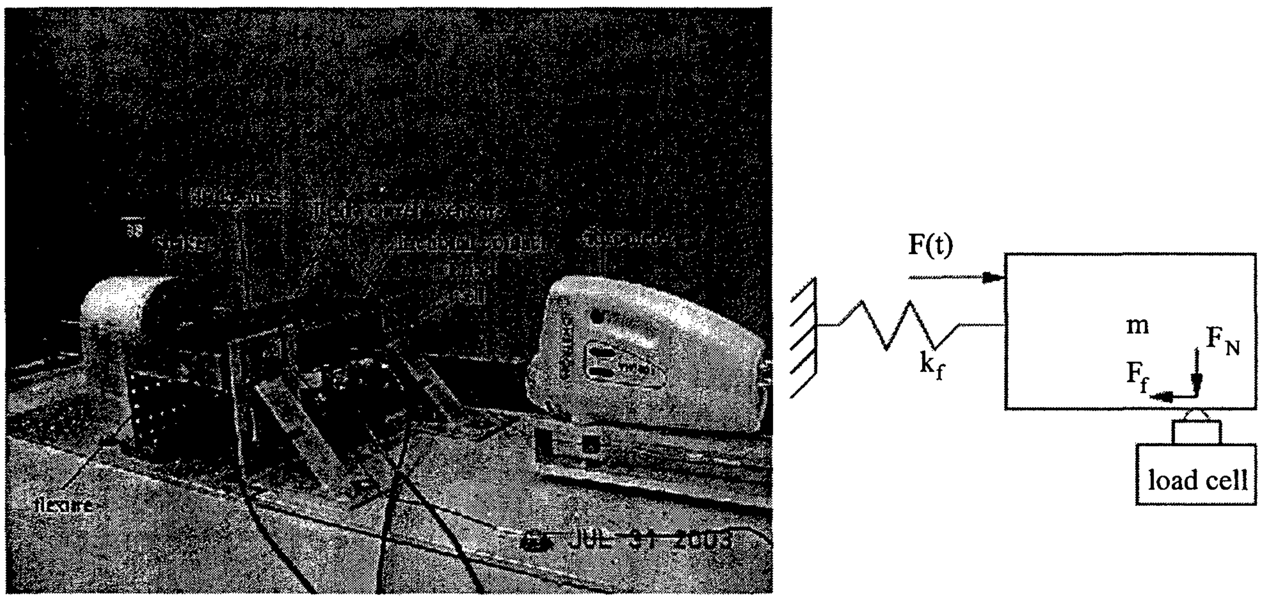
3. Significant Accomplishments/New Findings

3.1. A Microslip Friction Oscillator: Slip Hysteresis on the Micrometer Scale

The "microslip oscillator" designed, built, and exhaustively tested in the course of this project has enabled a focus on interface constitutive laws and associated system dynamics relevant to the mechanics of partial and complete slip at micron scales. A photograph of the experiment is given in Figure 1, as is a schematic of the dynamical system associated with it. As can be seen, the upper half of the frictional interface tested is a rigid plate with an adjustable eccentric mass, excited harmonically, guided by a flexure, and sliding on a frictional

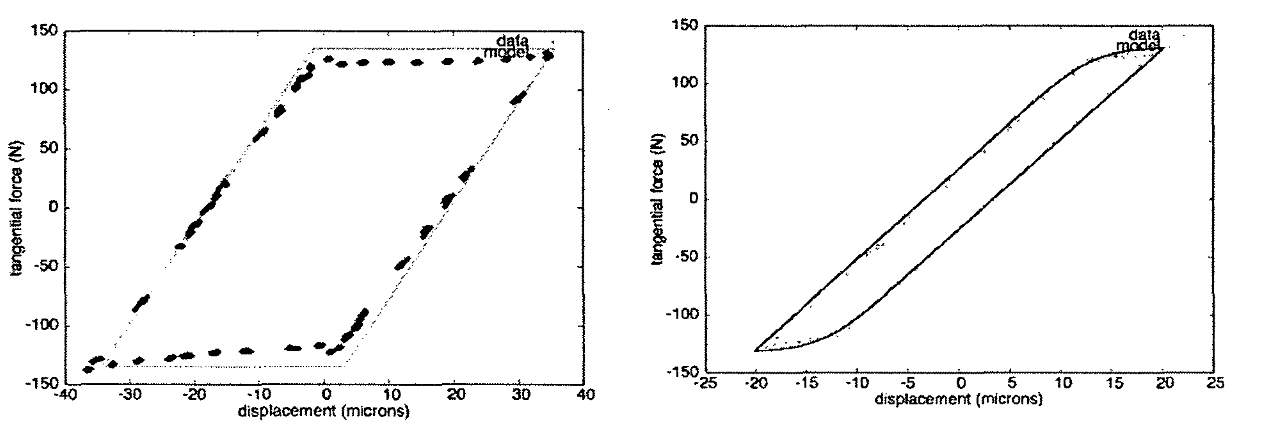
bearing, equipped with a tri-axial load cell. We have used both laser vibrometry and eddy current sensors to precisely cross-calibrate motion measurements, to determine interface compliances, and to measure the relative deformation and slip motion across this frictional interface. The flexure simply and effectively constrains motion to two degrees of freedom: longitudinal in the direction of the external force and rotational about a vertical axis.

The major development in this research was to demonstrate the reliable measurement of both partial and total slip hysteresis loops on this (cylindrical) Hertzian contact, which enabled the careful correlation with numerical prediction to be discussed further below. Representative examples are to be seen in Figure 2. Although work done in this study concentrated on one-dimensional slip trajectories, future efforts will focus on intermittent stick-slip cycles with slips in the 10 to 20 micrometer range, elliptical slip orbits, and a more extensive analysis of frequency, amplitude, and history (wear-in) dependence.



(a) (b)

Figure 1. Microslip Oscillator Experiment: (a) photograph of test setup; (b) schematic of setup. A plate is mounted on the bottom of the mass, and a cylindrically-tipped contact is mounted on top of the load cell. Eddy current sensors and laser vibrometry are used to enable measurement of very small slips occurring across this plate-cylinder junction of this Hertzian contact (often less than 10 microns).



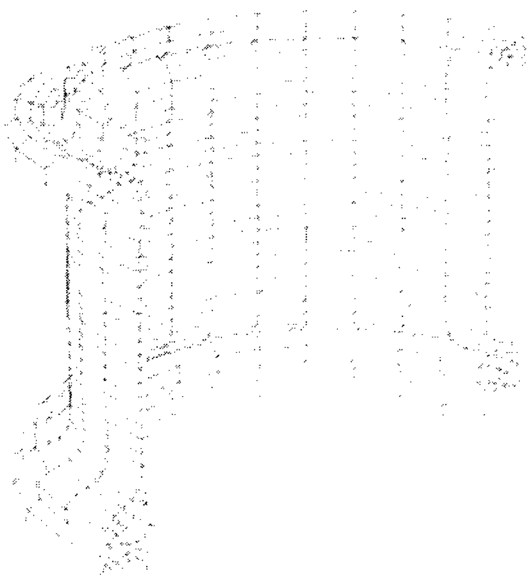
(a) (b)

Figure 2. Microslip Oscillator Experiments: typical hysteresis loops measured. (a) is an example of "macroslip", where the entire Hertzian interface tends to slide at once; (b) is a microslip hysteresis loop, where a stick-slip transition occurs on the Hertzian contact patch during a load cycle.

3.2. New Mortar-Based Surface-to-Surface Contact Algorithms for Frictional Contact

In fact, the result in Figure 2(b) demonstrates a fundamental premise of this research: at very small slip distances, even a very localized frictional contact (in this case, a Hertzian contact) can exhibit a complex combination of elastic compliance and frictional sliding behavior, which manifests itself in this case by an apparent hardening behavior. Successful prediction of hysteresis in such settings requires the modeling not only of interface behavior, but of the interaction of this behavior with models of compliance in the contacting bodies. One of the major accomplishments of this work is the development of a new mortar-finite element method for treatment of contact between compliant surfaces (elastic or otherwise), which uses results from the domain decomposition literature to assure unprecedented numerical accuracy for interface problems. Some examples of the type of simulations we routinely perform using this technique are given in Figure 3; in the next section, we will describe results obtained by application of this new methodology specifically to the microslip situation. It should be noted that this technique has two distinct advantages over existing methods: it is far more accurate (a necessity for resolving the hysteretic details of interface response), and it tends to be far more robust as well.

(a)



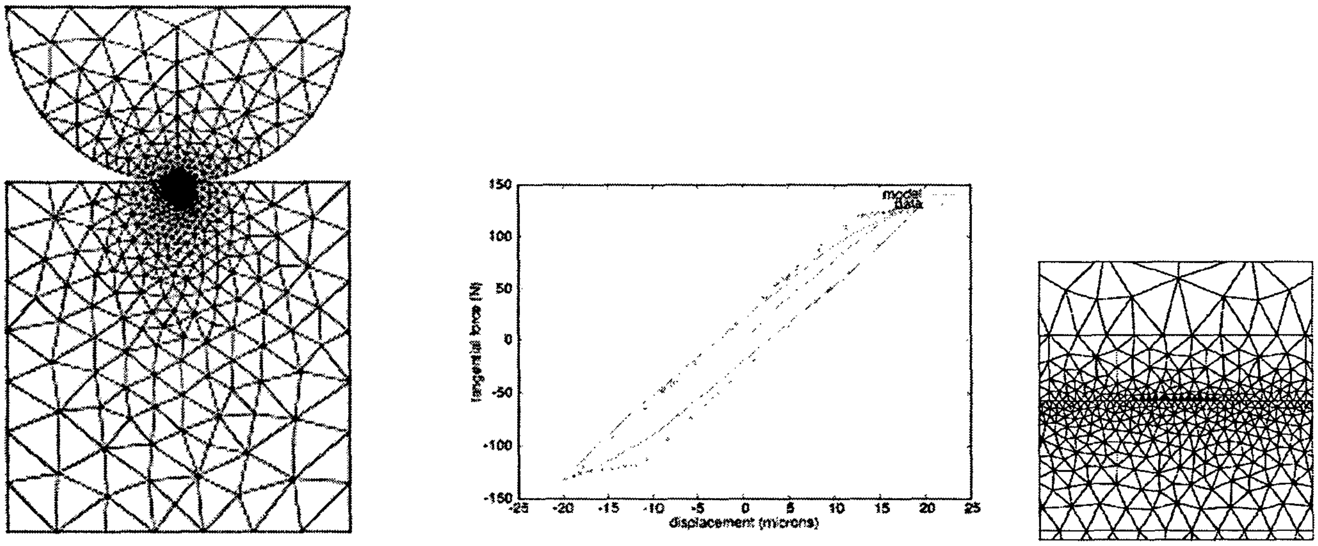
(b)

Figure 3. Examples of applications using the mortar surface-to-surface contact algorithm in finite element simulations of frictional contact: (a) a two-dimensional, three-body elastodynamic problem in which gaskets both contact each other and also self-contact; (b) a three dimensional cylinder post-buckling application. Neither of these simulations run reliably using traditional numerical formulations of frictional contact.

3.2. Integration of Experiment and Finite Element Modeling of Microslip: Successful Prediction of Partial Slip Hysteresis

The most significant accomplishment during the last year of this project was the successful application of the mortar-based numerical methods we developed to the microslip problem, allowing *a priori* modeling of slip hysteresis in partial slip situations, without *ad hoc* model parameters (the friction model utilizes only a coefficient of friction and interface stiffness). Figure 4 shows a typical finite element model of the Hertzian

contact in our microslip experiment, and also gives a typical prediction of the finite element model of global hysteresis. The "rounding off" of the hysteresis loops is produced by partial slip situations on the interface, which the numerical method must be able to resolve. The zoom in the figure shows how our numerical method is able to resolve such local details in the simulation.



(a) (b) (c)

Figure 4. Finite element prediction of measured microslip hysteresis, using direct simulation as opposed to phenomenology: (a) unstructured mesh of Hertzian contact, enabling high resolution of contact zone; (b) comparison of model prediction to experiment; (c) zoom of contact region; contacting zone is darkened in black.

4. Personnel Supported

Personnel involved with this project were:

- Tod A. Laursen (PI), Professor, Department of Civil and Environmental Engineering, Duke University
- Henri P. Gavin (co-PI), Associate Professor, Department of Civil and Environmental Engineering, Duke University
- Lawrence N. Virgin (co-PI), Professor, Department of Mechanical Engineering and Materials Science, Duke University
- Ryan Greer, Graduate Research Assistant, Department of Mechanical Engineering and Materials Science, Duke University
- Bin Yang, Graduate Research Assistant, Department of Civil and Environmental Engineering , Duke University
- Teresa Tetlow, Undergraduate Research Assistant, Department of Mechanical Engineering and Materials Science, Duke University

5. Publications

Works produced during this project, with direct relevance to it, were:

Greer, R., Gavin, H.P., Laursen T.A. and Virgin, L.N. (2004), "Dynamic micro-slip friction: experiments and modeling," in preparation.

Yang, B. and Laursen, T.A. (2005), "A Contact Searching Algorithm for Large Deformation, Finite Sliding Mortar Formulations," submitted.

Yang, B. and Laursen, T.A. (2005), "A Large Deformation Self-Contact Mortar Formulation with Finite Sliding," submitted.

Laursen, T.A. & I. Stanciulescu (2004), ``An Algorithm for Incorporation of Frictional Sliding Conditions Within a Steady State Rolling Framework," *Communications in Numerical Methods in Engineering*, to appear.

Yang, B., T.A. Laursen & X.N. Meng (2004), "Two Dimensional Mortar Contact Methods For Large Deformation Frictional Sliding," *International Journal for Numerical Methods in Engineering*, **62**, 1183-1225.

Puso, M.A. & T.A. Laursen (2004), ``A Mortar Segment-to-Segment Frictional Contact Method for Large Deformations," *Computer Methods in Applied Mechanics and Engineering*, **193**, 4891--4913.

Puso, M.A. & T.A. Laursen (2003), "A Mortar Segment-to-Segment Contact Method for Large Deformation Solid Mechanics," *Computer Methods in Applied Mechanics and Engineering*, **193**, 601--629.

Laursen, T.A. & M.W. Heinstein (2003), ``Consistent Mesh Tying Methods for Topologically Distinct Discretized Surfaces in Nonlinear Solid Mechanics," *International Journal for Numerical Methods in Engineering*, **57**, 1197--1242.

Love, G.R. & T.A. Laursen (2003), "Improved Implicit Integrators for Transient Impact Problems---Dynamic Frictional Dissipation Within an Admissible Conserving Framework," *Computer Methods in Applied Mechanics and Engineering*, **192**, 2223--2248.

Puso, M.A. & T.A. Laursen (2003), "Mesh Tying on Curved Surfaces in 3D," *Engineering Computations*, **20**, 305--319.

M.W. Heinstein & T.A. Laursen (2003), "A Three Dimensional Surface-To-Surface Projection Algorithm for Noncoincident Domains," *Communications in Numerical Methods in Engineering*, **19**, 421--432.

Additionally, Ryan Greer's Masters thesis was completed in December of 2004, and was made possible by the support of this project; the citation to that is as follows:

Greer, R. (2004), *Experimental and Numerical Investigation of Microslip*, MS Thesis, Department of Mechanical Engineering and Materials Science, Duke University.

6. Interactions/Transitions

6.1. Participation/presentations at meetings, conferences, etc.

As mentioned elsewhere in this report, this research project is a collaborative effort with AFOSR Grant number F49620-02-1-0039, headed by E. Berger of the University of Cincinnati. We have held several technical meetings involving the personnel from both projects during this collaboration:

- April 3, 2002, at the University of Virginia in Charlottesville, VA. Attendees: E. Berger (University of Cincinnati); M. Begley (University of Virginia); T. Mackin (via teleconference, University of Illinois); T. Laursen (Duke University); L. Virgin (Duke University); H. Gavin (Duke University
- September 10, 2002, at Duke University in Durham, NC. Attendees: E. Berger (University of Cincinnati); M. Begley (University of Virginia); T. Mackin (University of Illinois); H. Inglis (University

of Illinois); T. Laursen (Duke University); L. Virgin (Duke University); H. Gavin (Duke University); R. Greer (Duke University)

- February 18-19, 2003, with February 18 spent at the University of Cincinnati (Attendees: E. Berger (University of Cincinnati); D. Deshmukh (University of Cincinnati; M. Begley (University of Virginia); H. Inglis (University of Illinois); T. Laursen (Duke University)) and February 19 spent meeting with GE Aircraft Engines personnel (led by Dr. Matt Weaver)
- D. Deshmukh from the University of Cincinnati visited Duke University to discuss his results pertaining to this project on March 24, 2003.
- T. Laursen met with T. Mackin and E. Berger at Santa Fe, NM in October of 2003, at the AFOSR Structural Mechanics Program review.
- T. Laursen, H. Gavin and L. Virgin met with E. Berger at Wintergreen, VA in August of 2004 at the AFOSR Structural Mechanics Program review.
- T. Laursen met with E. Berger at Albuquerque, NM in February of 2005 at a Sandia/NSF program workshop.

In addition to presentations reported in earlier years, two conference presentations have been made by T.A. Laursen this year with relevance to this project:

- Laursen, T.A., "Mortar-Based Surface-to-Surface Contact Algorithms in Large Deformation Solid Mechanics" (keynote lecture, invited), Fourth Contact Mechanics International Symposium, Hannover, Germany, July 4--6, 2005.
- Laursen, T.A., "Mortar Elements in Large Sliding Frictional Contact Analysis," 16th International Conference on Domain Decomposition Methods, New York, New York, January 11-15, 2005.

Several other relevant presentations had T.A. Laursen as a co-author, but were given by others.

6.2. Consultative and advisory functions to other laboratories

Tod Laursen served as a consultant to Lawrence Livermore National Laboratory, a DOE laboratory administered by the University of California, for a two week period in July of 2005. The focus of his consulting was development of implicit finite element solution techniques for frictional contact problems, and the technical contact at LLNL was Dr. Michael Puso.

6.3. Transitions

We met with Dr. Matt Weaver of GE Aircraft Engines in February of 2003, and have been involved in periodic discussions with him about our research in general, and specifically about the material combinations which will be tested in our microslip friction oscillator experiment. Also, Henri Gavin has been involved in a colloboration with E. Dowell as an extension of the latter's Air Force project, which has been funded by the Lord Foundation.

7. New Discoveries, Inventions or Patent Disclosures

None to report at this time.

8. Honors/Awards

None to report at this time.